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SUMMARY TECHNICAL REPORT ON

TRANSIENT PRESSURE MEASURING METHODS RESEARCH

For the Period 1 March 1961 through 31 December 1962

(NASA CR-51515; Aeronautical Engineering Report No. 595F) OTS: $4.60ph, $1.52 mf

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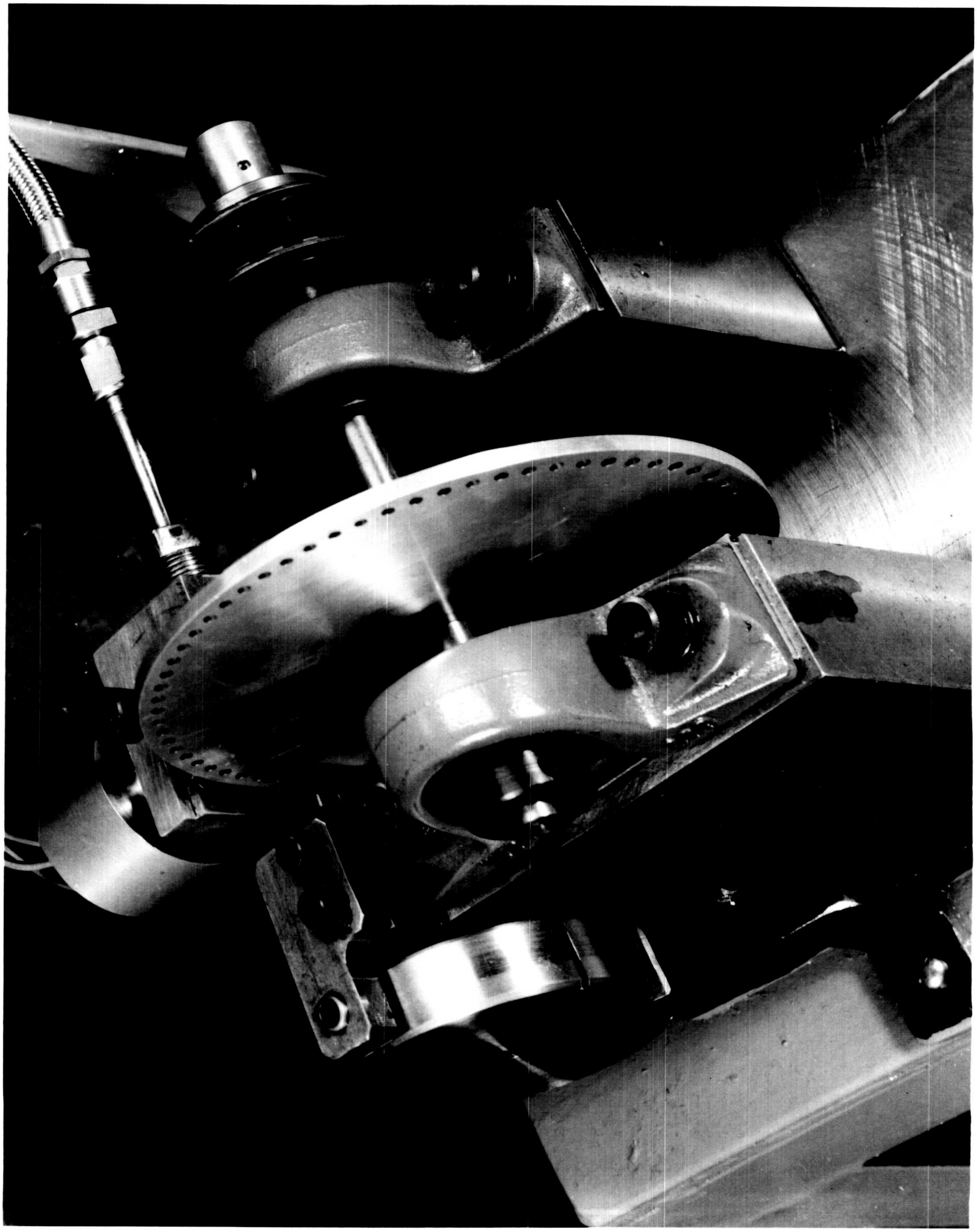

Sinusoidal Pressure Generator

FRONTISPIECE

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FIGURES

I. INTRODUCTION

During the twenty-two month period (1 March 1961 through 31 December 1962) covered by this report, an effort that has long been needed in the aerospace propulsion field was undertaken. Workers in liquid propellant rocket research and development have been aware for some years that the pressure measuring instruments used in evaluating combustion dynamics, including high frequency instability, were inadequate in a number of respects. Practically all of the water cooled, high frequency response transducers suitable for liquid propellant rocket combustion chamber application exhibited a characteristic pattern of strength and weakness that rendered satisfactory service under certain operating conditions and under other conditions would show quite different performance, none were completely satisfactory for service at chamber pressures of 1000 psig and above in the presence of fully-developed, high frequency combustion instability. Although some transducers came to be accepted as standard in various laboratories or test installations, the procurement specifications, manufacturers' claims and performance requirements were often at rather wide variance, although it should be understood that such transducers have necessarily been considered as specialty items by instrumentation manufacturers because of the low volume of their sales.

Experimental research in liquid propellant rocket combustion instability at Princeton over the past ten years has given us a special insight into the problem of making accurate measurements of transient pressures. In addition, we have been largely unsuccessful in our efforts to obtain instability data susceptible of theoretical analysis from industry or other laboratories. Also our familiarity with transducer design, fabrication and development problems resulting from long-term relations with personnel of the MIT Instrumentation Laboratory and later with their commercial enterprises and with the instrumentation business generally. All of this background equipped us to attempt a significant contribution in this scene as described below.

We saw our function in the Guggenheim Laboratories at Princeton to be one of identifying the characteristics required in a transducer based on a knowledge of pressure measuring requirements and instrument design possibilities and, in addition, evaluation of transducers and their systems specialized laboratory tests utilizing apparatus developed at Princeton and, finally, by rocket motor tests under conditions of fully-developed high frequency instability in our test rocket chambers. In addition, we hoped to accelerate the development of advanced transducers by supporting interested instrument manufacturers in the prototyping and development of a new transducer or in the improvement of an existing transducer. Also our experience led us to some new ideas on transient pressure measurements under certain conditions associated with specific applications.

It was also apparent that an educational effort needed to be made throughout the aerospace field to acquaint engineers and others with the factors involved in the dynamic response of transducers and their measurement systems. A list of publications so far resulting from our research is included in this report as Appendix A. The first two publications (1 and 2)* were issued during the time that Mr. H. B. Jones, Jr. was research leader. The first presents theoretical and experimental data

*Numbers in parentheses refer to the List of Publications included in Appendix A.

on the effects of tubing connection on transducer response. The second is an excellent summary of the fundamentals of transient pressure measurement as applied to rocket combustion chambers.

The sections below present the further results from the research during the period of this report in summary form.

II. FLUSH DIAPHRAGM TRANSIENT PRESSURE TRANSDUCERS FOR CURRENT LIQUID PROPELLANT ROCKET COMBUSTION CHAMBERS

A number of transducers are available for the measurement of transient pressures in current liquid propellant booster rocket combustion chambers. These usually employ a flush water-cooled diaphragm as the pressure sensitive element and are designed for use up to about 1200 pounds per square inch combustion chamber pressure with associated heat fluxes that range up to 25 BTU/in^{2}sec during unstable operation of the chambers. None of the available transducers is completely acceptable for this service for various reasons as established by our preliminary evaluations (3). The available transducers that were given the preliminary evaluations are listed in paragraph I in Appendix B and the current transducers, including some with diaphragms modified as a result of this research that will be evaluated during the next period are listed in paragraph IIA of the same Appendix. Some other methods of measuring transient pressures are also listed in this Appendix as well as advanced transducers that will be evaluated at a future time (see paragraph III).

A. Current Transducer Evaluations

Transducer evaluations in the next period will be carried out according to written procedures that have been developed during the period of this report. The current form for this purpose is included herein as Appendix C. Comments on this procedure are desired as it will be subject to continued revision for sometime to come. Further development of each of the evaluation tests is underway and it is already planned to add additional sections, such as Vibration Testing, as soon as possible.

The first step in the evaluation of a pressure transducer is thorough inspection. This consists of an overall visual check with emphasis on the condition of the diaphragm which is viewed under a forty power stereo-microscope. This often reveals cracks, scratches, small chunks of metal, etc. Experience has shown that any imperfection of this sort can represent an incipient failure. Diaphragms must, therefore, be smooth and uniform in appearance.

The transducer is next measured dimensionally to insure that it will fit the provided mountings. The manufacturer's outline drawings are used as the standard of comparison.

Resistance measurements are then made at the electrical output terminals of the transducer. Resistance between the terminal(s) and ground should be 10^9 ohm for transducers of the strain gage type and 10^{13} ohm for those of the piezoelectric (quartz) type. Certain other types have a grounded internal structure, in which case the leakage resistance measurement is not applicable. Input and output resistance is next measured, a step which applies principally to strain-gage devices.

As an example, we will follow a typical pressure transducer through the evaluation procedure. Dynisco Model PT49 AF-IM, Serial No. 14996 has been chosen. This pickup exhibited a leakage resistance of infinity (i.e., greater than 10^9 ohm) and an input resistance of 355.8 ohm. Output resistance is of importance mostly so that one can check for subsequent changes. In this case it was 323.9 ohm.

Following the resistance checks, water is flowed through the transducer, and a visual check is made for coolant leaks. Another leakage resistance check is then made to detect the occurrence of an internal coolant leak. Number 14996 showed neither external nor internal leaks. The passages were then purged of coolant and the transducer made ready for static calibration.

Static testing consists of loading the pickup through its pressure range and recording the output voltages. This is done twice with dry, open coolant passages, and once with coolant flowing at rated conditions. The data are fed to a computer which determines the slope of the best straight line through the points, the y-intercept (zero pressure output) and the root-mean-square error. The slope as indicated by the first run was 0.29935 millivolts/psi against 0.029934 millivolts/psi for the second run both with an rms error of 0.01%. This represents a repeatability of 0.003% for the slope and 0.001% for the y-intercept. Such figures are well within the specifications of the manufacturer, and are, in fact, beyond the resolution of our calibrator. Application of coolant flow has an effect of -0.4% on slope, and -0.4% on the y-intercept.

A drift test is next performed. This procedure consists of observing the zero pressure output, with normal coolant flow applied at 10 minute intervals for a two hour period. The only change observed was 0.01 millivolt which is essentially zero drift.

The above procedure is usable for transducers measuring relatively slow changing pressures. In general, it may not be assumed that the input-output relation determined statically will hold true for the dynamic case. Dynamic testing is seldom ideal, that is, it seldom reproduces exactly the conditions of usage.

For dynamic measurements the evaluation procedure relies upon the shock tube and the Sinusoidal Pressure Generator. The shock tube yields rise time, natural frequency, and damping ratio directly, while the response with frequency must be obtained from Fourier analysis usually involving a computer. The SPG yields directly a response curve vs applied frequency. In reality the same basic parameters can be obtained with either test method, but the response data is more readily available as furnished by the SPG. It has been shown that for a given transducer response curves derived from the shock tube and the SPG are in good agreement. An MSE thesis on the response of a small chamber which is the basic element of the SPG has been completed (4) and another is currently in progress on the dynamic response testing of transient pressure transducers for liquid propellant rocket combustion chambers using the shock tube and SPG techniques.

The shock tube testing is conducted as follows. The transducer is end mounted in the shock tube and a 500 psi burst disc is installed. A pressure step of 375 psi for four milliseconds is obtained at the transducer diaphragm. This is an adequate duration for testing any transducer with at least a 1 kc natural frequency. Typical transient pressure transducers have a natural frequency well above this value. In the particular instance illustrated here the Dynisco transducer PT49 AF-IM, Serial No. 14996 exhibited a natural frequency of 23 kc and a damping ratio of .06 of critical. Rise time was 8 microseconds. Certain approximate conclusions may be drawn from these few observations. One, the transducer will be usable up to about 1/3 of the natural frequency; i.e., up to about 8 kc, without major corrections for amplitude or phase. Also, since the damping is far below critical, the sensor will ring during its usage on a rocket chamber. In most applications this natural or ringing frequency should be filtered out electrically. A low damping factor is typical of this class of transducers and is far below the ideal, which is critical damping. The measured rise time of 8 microseconds is consistent with the natural frequency of 23 kc according to theory.

The SPG procedure seeks to plot an actual response curve directly.

Here the transducer is mounted in a small chamber and subjected to pressure oscillations of known frequency and amplitude as described in (4) and shown in the FRONTISPIECE. Sinusoidal pressure signals ranging from 35 psi peak to peak at 1 kc to 6 psi P-P at 10 kc are applied to the diaphragm of the test sensor, and simultaneously to a monitor transducer. The ratio of the two transducer outputs is then calculated for each integral value of frequency from 1 kc to 18 kc. In the case of our illustrative pickup the pattern is as predicted from the shock tube test. Response is flat up to 4 kc, at which point it rises gradually to 12% at 8 kc. It then shows a small resonant peak at 10 kc. Beyond 14 kc the response rises rapidly, approaching the primary resonance at 23 kc.

Heat transfer tests are conducted in the laboratory using an open oxy-acelylene flame around 2 BTU/in^2 sec and in a rocket motor operating unstably with heat fluxes up to 15 BTU/in^2 sec. These tests provide data on the susceptibility of the transducer to the effects of heating on both the diaphragm and body and prove the suitability of the transducer under the specific test conditions. Test methods to predict burnout heat flux and more severe (i.e., higher chamber pressure) rocket motor tests are required to adequately evaluate this important feature. Our current test methods are described in more detail in Section III below.

B. Development of Advanced Transducers

When it became apparent that the current transducers discussed above could not meet the requirements adequately, target characteristics were prepared to define the goals toward which development work should be aimed. A version of these Target Characteristics is included herein as Appendix D, which is considered to be the best compromise possible at the present time between the requirements for transient pressure measurements in current liquid propellant combustion chambers of booster rocket engines and the state-of-the-art of transducer technology. Based on our contact with the instrumentation industry, we will support during the next period the development of advanced transducers specifically aimed at meeting the above-mentioned target characteristics by purchasing a number of prototypes of the transducers shown below:

1.	Dynisco PT-134	Bonded Wire Resistance Strain Gage Type
2.	Dynisco PT-501	Semi-conductor Strain Gage Type
3.	Elastronics EBL	Piezoelectric (Quartz) Type

On the delivery of these prototypes we will carry out evaluations on the basis of which the transducers will be modified as necessary until their development has been fully realized. We are also much interested in obtaining any other transducers for evaluation that may have characteristics approximating to a greater or lesser degree those presented in Appendix D. We are also anxious to consider any revision of the Target Characteristics that will better delineate a more satisfactory transducer for the stated purpose.

III. TRANSDUCER HEAT FLUX CAPABILITY

At the present time the lack of any transducer with the demonstrated ability to withstand heat fluxes of 25 BTU/in^2 sec and above, which is representative of the conditions produced by fully-developed, high frequency combustion instability at chamber pressures around 1000 pounds per square inch using conventional propellants, can probably be considered the most fundamental transducer shortcoming. A large amount of effort has gone into the effort to improve the ability to keep from burning out the very thin diaphragms by circulating a large coolant water flow at elevated pressure through small and rather torturous passages with a respectable velocity and without local cavitation or recirculation which would produce hot spots and lead to burnout. Our report, "Transient Pressure Transducer Design and Evaluation" (2) describes the situation quantitatively.

The importance of the selection of diaphragm material and thickness is also discussed in (2) from a number of standpoints. One very promising diaphragm material is nickel and transducers utilizing it have received preliminary testing during this period, although some fabrication difficulties were experienced.

A. Evaluation of Current Transducers

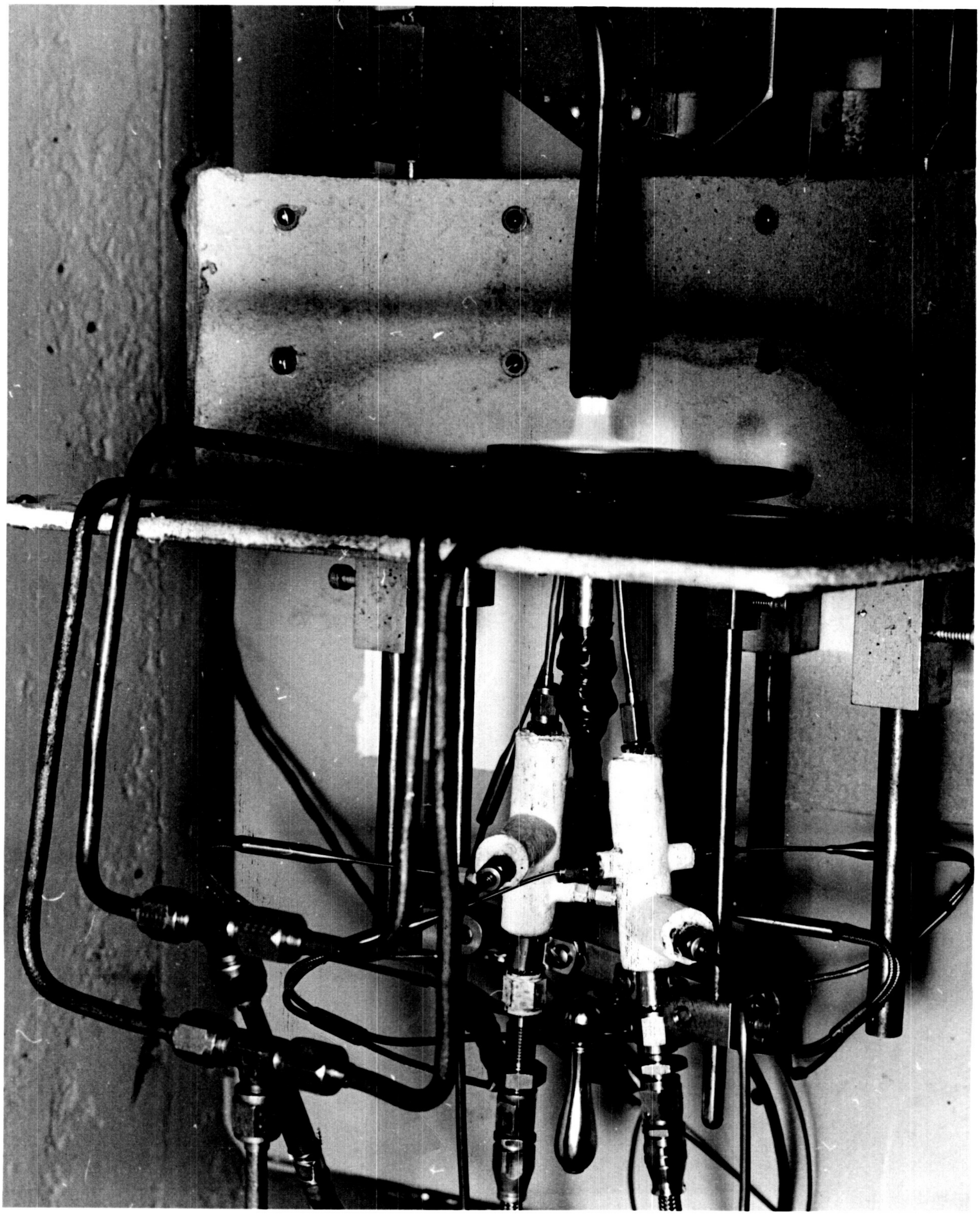
Both laboratory tests to establish a transducer's basic behavior when subjected to a precision heat input and rocket motor proof tests are needed to evaluate the ability of a transducer to provide a satisfactory output despite a severe thermal environment. The next two subparagraphs describe our heat flux capability tests in some detail.

1. Laboratory Tests

Open flame tests were performed using a multi-flame oxyacetylene torch as a heat source with a water-cooled adapter to hold the transducers as shown in Figure 1. As suggested in (2), it is advantageous to test initially at a heat flux value considerably lower than that available in rocket motors. A heat flux of 2 BTU/in^2 sec and an average coolant pressure at 75 psig were chosen as nominal test conditions for all transducers being evaluated. Data repeatability was difficult using a peripherally-cooled copper heat sink and some of the difficulty was traced to an uncontrolled transducer body temperature. As a consequence a water-cooled adapter (Drawing No. JP24 L2006A) was designed to control body temperature within $\pm$ 2°F over a wide range of heating conditions. Coolant temperature increase is small at this nominal level of heat flux but the flow rates increases of from four to six percent at the same pressure drop are probably caused by a change in coolant water viscosity; it was also necessary to design special coolant Δ p Δ T fittings (Drawing No. JP24 S2009A) to get repeatable coolant pressure drop and temperature rise data. These manifolds make possible temperature difference measurements within 0.1°F, and pressure drop can be set accurately and monitored to assure a constant average diaphragm coolant pressure.

Other laboratory testing consisted of increasing average coolant pressures at the above heat input rate until failure occurred and dead-weight testing at various average coolant pressure levels. These tests established the present coolant pressure limits for different diaphragm materials and provided a comparison of strength and reliability after severe internal strain. A new coolant system that will permit higher coolant pressure operation using distilled water is being installed in an effort to improve the precision of our heat transfer tests from this standpoint.

An effort was made to determine pressure and velocity gradients



Open Flame Heat Transfer Test of a Dynisco PT49AF-IM Transducer

FIGURE 1

across a maze-type diaphragm coolant passage with good results. Using transducer bodies with the diaphragm removed, pressure drop across the maze was determined by establishing the pressure losses in the inlet and outlet tubes and body passages. Standard flow calculations were employed taking into account the changing geometry through the maze. Results fell within 2 psi of measured flow data lending credence to calculated velocities for individual sections of the maze, as shown in Appendix E.

2. Rocket Motor Tests

The effects of coolant flow rate, average coolant pressure, and velocity during rocket motor tests could not be studied in any great detail during this period since rocket motor operations did not cover the necessary conditions. Heat fluxes ranged from 3 to 13 BTU/in^2 sec with coolant flow rate and average diaphragm pressure at 0.055 lb/sec and 75 psig, respectively. A burnout occurred at a heat flux of approximately 10 BTU/in^2 sec on a transducer using Type 347 stainless steel as the diaphragm material. This occurred at a low chamber pressure and is attributed to improper transducer location in the motor and with respect to the injector configuration. No other failures have been recorded, although Type 347 and 17-7 PH stainless steels and Type A nickel were used as diaphragm materials. Runs were made under unstable conditions at chamber pressures of 150, 300 and 600 psi with frequencies ranging from 250 to 3,000 cps and pressure amplitudes from 25 to 300 psi. To test the heat flux capability of the transducers adequately, chamber pressures must be increased and rocket operating conditions prescribed.

Rocket motor tests on transducers having Type A nickel as diaphragm material showed marked corrosion of the diaphragm after 5 to 10 seconds of run time. Coating of 0.0002 inch and 0.0005 inch thicknesses of chrome plating checked corrosion with no apparent change in transducer performance. There is analytical evidence that a 0.005 inch thick nickel diaphragm, protected from corrosion, will perform at the 25 BTU/in^2 sec heat flux level (2). For instance, at 1000°F the elastic limit is about the same as the nickel steels or approximately 15,000 psi. Thermal conductivity is about 2½ times that of Type 347 stainless steel indicating a smaller temperature drop for the same thickness and at the same heat flux. If coolant pressures and flow rates can be adjusted to provide required increased velocities, the important factor in the basic heat transfer equation becomes the thermal capacity of the coolant. Recent preliminary tests in the laboratory were aimed in this direction. Flow rates up to 0.1 lb/sec of coolant water were attained at pressures around 75 psig average diaphragm coolant pressure. At this flow rate the calculated velocity is about 42 fps in the center of the maze where it is lowest.

B. Research and Development Toward Higher Heat Flux Capability

Any material chosen for transducer diaphragms will be limited in one way or another. Thermal conductivity, strength and corrosion resistivity are the major factors. Work with metal and ceramic coatings has been initiated, as well as with "sandwich" diaphragms. This work will be tested first in the laboratory with final results subjected to rocket motor operation at high chamber pressures under unstable conditions (with accompanying high heat flux). A large increase in heat flux capability is anticipated with the use of ceramic, especially metallic oxide, coatings.

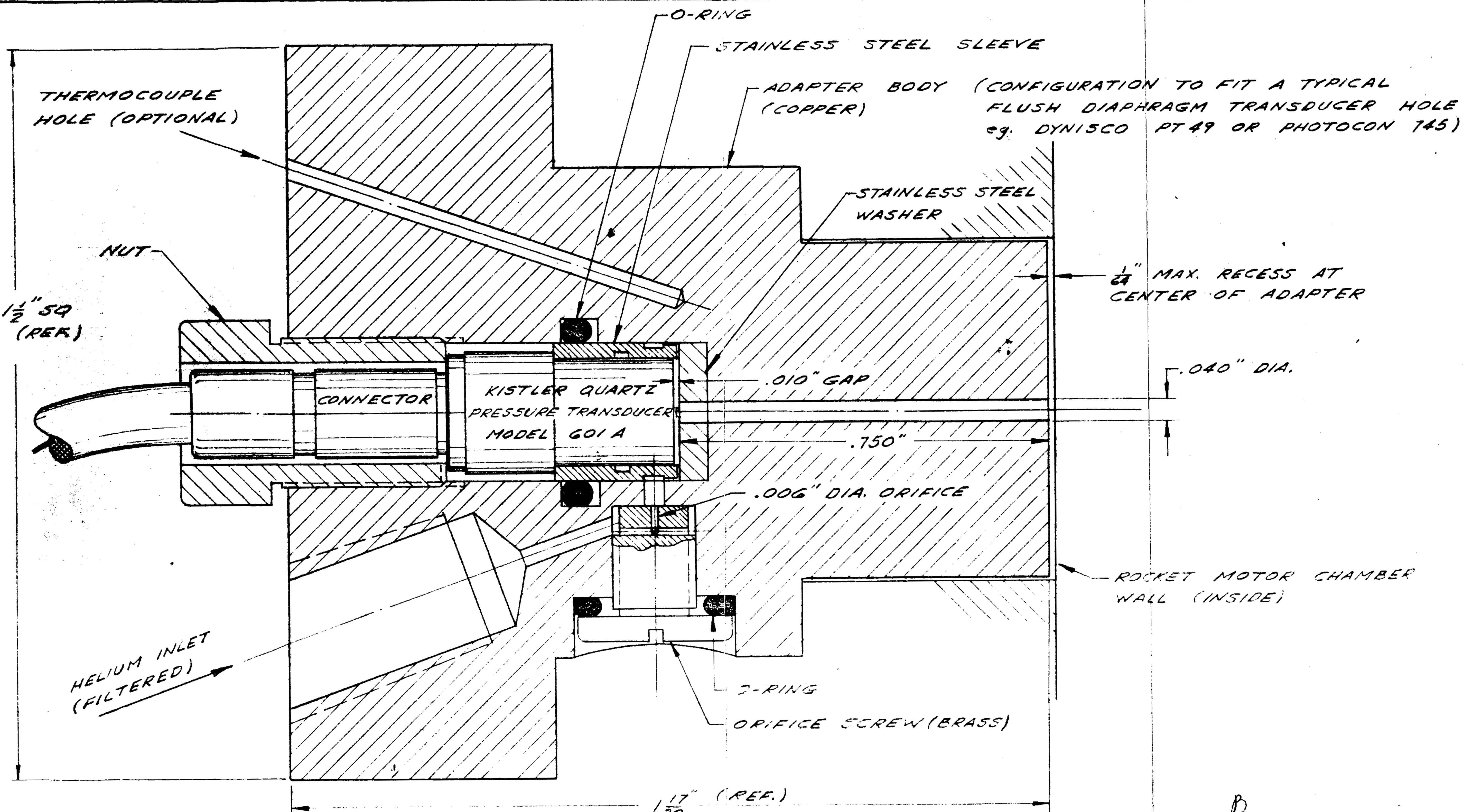
Coolant passages in present transducers must be modified or redesigned if cavitation and hot spots are to be eliminated. As the over-all size of a transducer is decreased, this becomes more of a problem. The maze type of coolant passage may have to be discarded for a more simple flow geometry. There is also the problem of available coolant supply pressure. It is always undesirable to employ a higher pressure than that available from the fuel or oxidizer system of a rocket motor, hence pressure drop upstream of the transducer diaphragm must be kept at a minimum. Admitting the coolant to the diaphragm area becomes a greater problem when transducer diameter is reduced. Coolants exhibiting a lower thermal capacity and in some cases a considerably higher viscosity than water may need to be used in practical development cases and must be considered.

IV. A SMALL PASSAGE TECHNIQUE FOR TRANSIENT PRESSURE MEASUREMENTS IN LARGE ROCKET MOTORS

A new technique for making transient pressure measurements in large rocket motors (5) where the response modes of interest are of relatively low frequency has been conceived and tested in several successive configurations. This technique makes use of the frequency response capabilities of a small passage 0.040 inches in diameter and 0.75 inches long leading from the combustion chamber to a small cylindrical volume 0.218 inches in diameter and 0.009 inches high into which helium is bled through an 0.006 inch diameter choked orifice. The volume diameter is sized to a Kistler 601A piezoelectric (quartz) type transducer. The configuration is shown on Drawing No. JP24 M016A which is presented herein as Figure 2.

The performance of this arrangement which is identified as the Small Passage Technique is shown in Figure 3 as measured by the Sinusoidal Pressure Generator. The essentially flat response up to 3000 cycles per second is understood to be adequate for instability modes of current interest in the F-1 combustion chamber and the configuration should be ideal for installation in the cooled thrust chamber wall either between tubes or through the center of a tube.

Further research and development effort will be placed on this technique during the coming period and it is expected that it will be possible to provide extended performance and even more practical configurations. Additional details on the initial work were included in Princeton University Aeronautical Engineering Report No. 595e (5) which had only a limited distribution. A technical report will be issued when the technique has been more fully developed.



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GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO. JP 24 M 016 A			

FIGURE 2

FORM NO. 3765-2 D & W BLUEPRINT CO.

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Department of Aeronautical Engineering
Guggenheim Laboratories for the Aerospace Propulsion Sciences

JP 24 TRANSIENT PRESSURE MEASURING METHODS RESEARCH

Small Passage Technique (Kistler 601A in Adapter 14F)

Response Ratio vs Frequency

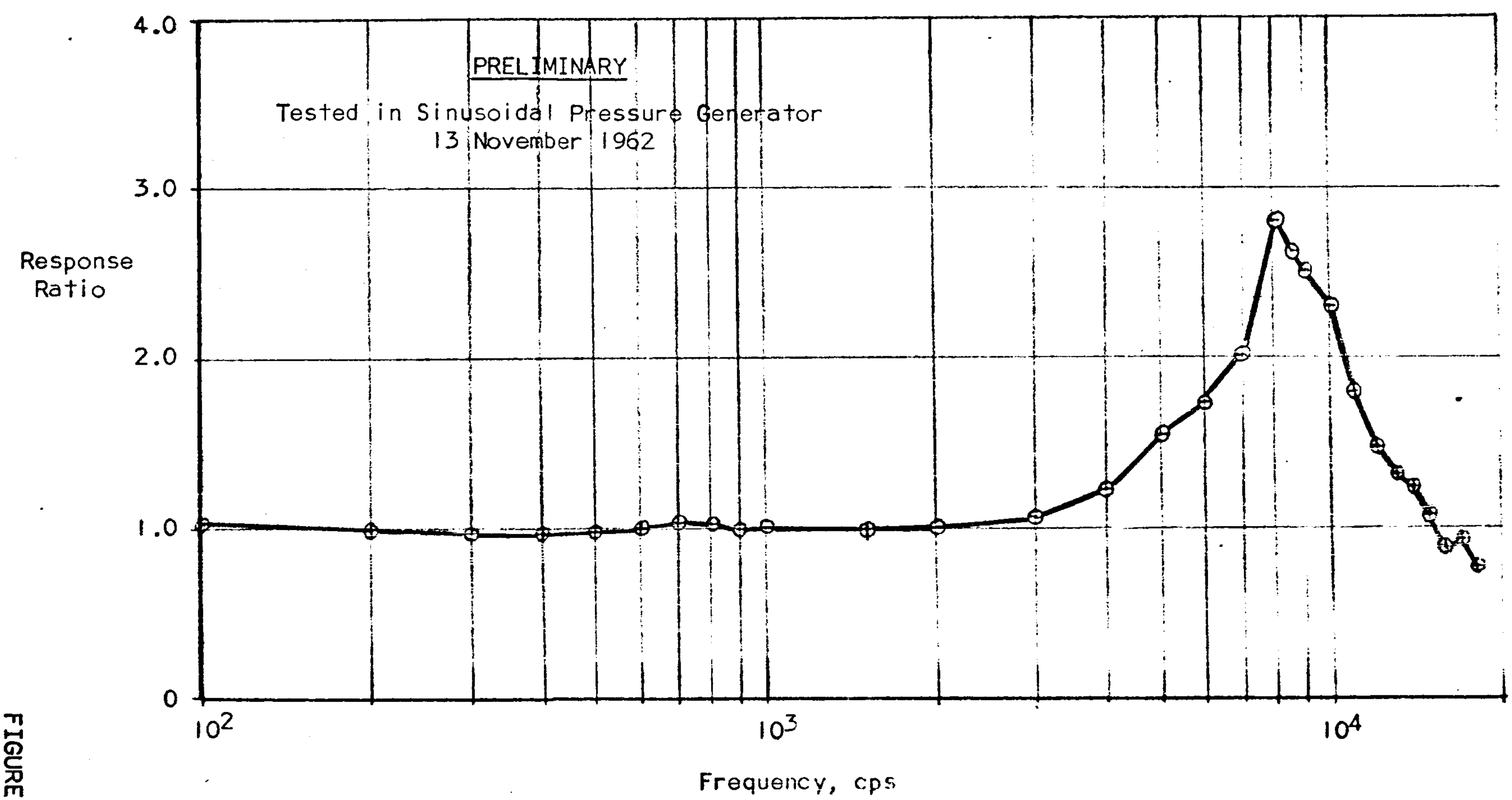

FIGURE 3

V. RESPONSE OF TUBING CONNECTED PRESSURE TRANSDUCERS

Often, when instrumenting a rocket chamber for transient pressure measurement, a flush diaphragm transducer is not employed. The usual alternative is a cavity-type transducer connected by several inches, or even several feet of tubing. The resultant configuration of tubing plus instrument volume will yield a faithful record of pressure only under steady-state conditions. When oscillatory pressures are present both average and transient pressures will be in error. Much testing of tube-volume configurations has been performed on the SPG. The usual pattern followed in transient measurement shows a resonant peak at some frequency with an amplitude of several times the actual pressure signal at the tube entrance. The response curve is generally considered to be flat ($\pm$ 10%) up to 1/3 the frequency of the first resonant point. It should be pointed out that the characteristics of such a configuration depend upon usually unknown gas properties in the tube and volume. This makes the calculation of the performance of such a system quite difficult. Experimental test of a given configuration using the SPG is conducted quite easily and accurately under conditions that indicate the response characteristics with some fidelity. Further work in extending the SPG technique for this kind of testing is under way.

Average pressures measured by the tubing-volume arrangement have been observed to display small errors. A typical measurement with a tubing length of 6 inches using helium as the test gas in the SPG showed a drop of 2 psi from an average pressure of 100 psi at a frequency of 1000 cps with a peak-to-peak amplitude of 30 psi. The effect is thought to be caused by a loss of acoustic energy due to the viscous forces in the fluid medium. A test program to further investigate these effects is under way.

VII. DYNAMIC RESPONSE TESTING OF TRANSIENT PRESSURE TRANSDUCERS FOR LIQUID PROPELLANT ROCKET COMBUSTION CHAMBERS

The need for evaluating a transducer and its system designed to make measurements over a range of frequencies from around 100 cps to 10,000 cycles per second under dynamic conditions would seem rather evident, but unfortunately too few workers have tested up to this time to be sure that a transducer and its auxiliary equipment as utilized in a system exhibiting non-steady pressures were free of resonance and other effects producing spurious signals. Workers at a number of agencies have undertaken in the past or are now undertaking the establishment of techniques and requirements for dynamic response testing. These include MIT, Edwards Air Force Base, Jet Propulsion Laboratory, NASA Lewis Research Center and Marshall Space Flight Center. Our efforts as described above include the utilization of a shock tube and the Sinusoidal Pressure Generator. Other methods of dynamic response testing have been used in the past and new means are appearing with some regularity. We are attempting to acquaint ourselves with all pertinent methods for transient pressure transducer evaluation. The results of this effort will be reported at a later time.

In addition to the laboratory tests much is to be learned from tests with a pulse gun in a rocket chamber both "cold" and "hot" with the transducer system completely connected. Tests of this sort have been planned and will be conducted during the next period.

VII. CONCLUSION

This summary report of progress from the initiation of research in transient pressure measuring methods as applied to liquid propellant rocket combustion chambers on 1 March 1961 through 31 December 1962 presents a number of elements of current interest in the aerospace propulsion field.

The evaluation and development of flush diaphragm transient pressure transducers for use in current large liquid propellant booster rocket engines is very badly needed and some progress has been made.

There is an immediate need to improve the heat transfer capability of the best of the present transducers by a factor of two or more, so they will withstand the very high heat flux (25 BTU/in^2 sec and above) produced by the liquid oxygen-hydrocarbon propellant combinations at current combustion pressures of around 1000 pounds per square inch under fully-developed instability conditions. Much more severe heat transfer problems will result from the even "hotter" propellants and higher pressures of the advanced booster rocket engines now in the research stage.

A small passage technique for transient pressure measurements whenever the frequency response requirements can be relieved somewhat has been tested. Further testing is now being conducted to extend the performance. This approach can become important as the fundamental factors are better understood and the practical application problems are clarified.

The dynamic response of tubing connected and flush diaphragm transducers to non-steady pressures has been investigated experimentally and analytically. Laboratory tests of transducers using a shock tube and a Princeton Developed Sinusoidal Pressure Generator and other special apparatus will continue and tests in pulsed rocket chambers both "cold" and "hot" have been planned and will be carried out during the coming period of research.

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APPENDIX C:
FORM NO. 93a

JP-24 EVALUATION PROCEDURE FOR FLUSH DIAPHRAGM TRANSIENT PRESSURE TRANSDUCERS

Date(s) of Test ______________

Type of Transducer: ______________________________

Manufacturer: ______________ Model: ________ Serial: ________

A. Inspection	Initial and Date
1. Inspect transducer for visual flaws or damage. View diaphragm with a stereo-microscope, noting cracks, dents, imperfect welds, etc. ____________________ ____________________	
2. Measure transducer for compliance with outline drawing. Note deviations.	
3. Measure leakage resistance from all active pins to ground using the volt-ohmyst on the R x IM scale. Leakage resistance = ______ megohm.	
4. For strain gage type measure input resistance using the Wheatstone bridge. Input resistance = ______ ohms.	
5. For strain gage type measure output resistance using the Wheatstone bridge. Output resistance = ______ ohms.	
6. Establish coolant water flow at rated conditions. Observe coolant flow rate at Rated inlet pressure ________ psig Rated flow rate ________ pps a. Observed outlet pressure ________ psig b. Inspect transducer for external coolant leakage	
7. Repeat Step 3 for leakage resistance. Leakage resistance = _____ megohm.	
8. Purge coolant passages of water.	

B. Static Testing	Initial and Date
1. Place transducer in dead weight tester and connect to auxiliary equipment if required. Follow manufacturer's procedures for the adjustment of the auxiliary equipment. Note control settings ____________ ____________ ____________	
2. Connect system to transducer calibrator and pressurize to full scale pressure. Note output level as indicated on transducer calibrator. If indicator is off-scale, insert an appropriate voltage divider to bring indication on-scale. Divider ratio = ____________	
3. Allow 30 minutes warm-up time unless manufacture recommends other.	
4. Apply pressure in 100 psi steps up to the full scale rating of the transducer and in an equal number of steps returning to zero pressure. Care should be taken to approach steps from the general direction of travel. This is to avoid any masking of hysteresis effects.	

	Applied Pressure (psig)	Output Voltage (mV)		Applied Pressure (psig)	Output Voltage (mV)
Ascending Pressure			Descending Pressure		

B. Static Testing (cont'd)	Initial and Date

5. Duplicate the above step to determine repeatability.

	Applied Pressure (psig)	Output Voltage (mV)		Applied Pressure (psig)	Output Voltage (mV)
Ascending Pressure			Descending Pressure		

6. Establish rated coolant flow and repeat Step 5.

	Applied Pressure (psig)	Output Voltage (mV)		Applied Pressure (psig)	Output Voltage (mV)
Ascending Pressure			Descending Pressure		

B. Static Testing (cont'd)	Initial and Date
Coolant pressure inlet ________ psig Coolant Pressure outlet ________ psig Coolant flow rate ________ psig	
7. Leave system connected and energized with coolant flow. Observe zero reading during a two hour period at 10 minute intervals.	

Time of Day	Zero (mV)	Time of Day	Zero (mV)	Time of Day	Zero (mV)

C. Dynamic Testing	Initial and Date
1. Shock Tube Testing a. Mount the transducer on the end of the shock tube in a suitable flange, taking care that the diaphragm is recessed 1/64" below the inner surface of the flange.	
b. Establish coolant flow through the transducer and allow adequate warm-up time.	
c. Insert a 500 psi burst disc in the shock tube and evacuate the downstream end of the tube.	
d. Bleed nitrogen into the downstream side of the tube until a vacuum of 17" of mercury is obtained. This corresponds to an 80:1 pressure ratio.	
e. Connect transducer output to the vertical input terminal of the scope and adjust the sensitivity so that nearly full scale deflection is obtained.	
f. Adjust sweep rate so that at least 10 cycles are obtained. Several shots may be needed to determine the proper settings of the scope controls.	
g. Photograph the display with the Polaroid camera and record the following information.	

Date	Time	Picture No.	Vert. Sens.	Horiz. Sens.	Rise Time (μs)	Nat. Freq. (cps)

C. Dynamic Testing (cont'd)	Initial and Date

2. Sinusoidal Pressure Generator

   a. Install the transducer in the wall of the chamber taking care that the diaphragm is recessed 1/64" from the chamber wall.

   b. Connect the test transducer output to an amplifier channel; thence to a Krohnhite band pass filter.

   c. Connect the monitor transducer through a parallel path as in Step b through a selector switch to the filter input.

   d. Connect the filter output to a Ballantine true rms voltmeter.

   e. Drive the generator at a speed corresponding to a frequency of 1000 cps. Adjust the amplifier gains to provide approximately equal signal levels into the filter.

   f. Holding all gain settings constant, collect multiples of 1 kc up to 20 kc and for each frequency record output level for each channel as indicated on the true rms meter. The band pass filters are to be reset for each excitation frequency, the limits being set at 3/4 and 4/3 of the excitation frequency.

Frequency (kc)	Monitor Output Voltage (mV)	Test Output Voltage (mV)

D. Heat Transfer Testing	Initial and Date
1. Open Flame Test.	
a. Install transducer with diaphragm recessed 1/64" in test block.	
b. Energize transducer and allow 30 minute warmup time.	
c. Check coolant supply level.	
d. Ice cold junctions and check instrumentation.	
e. Transfer coolant to high pressure tank.	
f. Coolant flowrate Vs. pressure drop data at prescribed average coolant pressure: Coolant manifold set number________.	

Coolant Pressures			Coolant Flowrate				
			Monitor		Potter		
P_1	P_2	dP	PPH	PPS	CPS	PPS	Remarks

g. Prescribed operation conditions:

Average coolant pressure, $\bar{P}_d$_____psig. Test block temp., °F______

Ox gas_____CFH, _____psig. Fuel gas______CFH, _____psig

Transducer position, D_____inches. Approx. Heat Flux___Btu/in^2 sec.

	Initial and Date
h. Check coolant level in high pressure tank. Transfer if necessary.	
i. Get data points 1 and 2 below. Ignite torch and complete test.	

j. Heat Transfer data:

Data Point	Coolant PPH CPS	PPS	T_1 °F	dT Div	°F	Heat Flux	Zero Shift Pressure Mv	Psi	Thermal Mv	Psi	Remarks
1											Coolant off.
2											Coolant on.
3											Heat on.
4											Heat off. Coolant off.

D. Heat Transfer Testing	Initial and Date
2. Rocket Motor Test. a. Install transducer in rocket motor with diaphragm recessed 1/64" from inner chamber wall.	
b. Attach coolant manifold not used for this evaluation.	
c. Energize transducer and allow 30 minute warmup time.	
d. Ice cold junctions and check instrumentation.	
e. Check coolant supply and set prescribed average diaphragm coolant pressure and flowrate. $\bar{P}_d$ ________ psig $\dot{w}$, lb/sec. ________	

f. Record data below

Oxidizer________ Fuel________ Run Number						
Chamber Pressure: Steady state, psig.						
Transient pk to pk, psig.						
Frequency of oscillation, CPS						
Mixture Ratio, OX/fuel						
Heat Transfer: Coolant flowrate, lb/sec.						
Coolant temperature difference, ^{o}F						
Body temperature, ^{o}F						
Heat transfer, Btu/sec.						
Heat flux, Btu/in^2 sec.						

Remarks:

APPENDIX D: Target Characteristics for Advanced Flush Diaphragm Transient Pressure Transducers for Measurements in Current Large Liquid Propellant Rocket Combustion Chambers

1. Application

a. The measurement of pressure transients in rocket combustion chambers is one of the more difficult problems in advanced metrology because a large number of onerous environmental conditions are present in combination with transducer mounting restrictions and high reliability requirements. The need for dynamic measurements is being felt increasingly in research and development testing and also in flight firings of rocket motors including those of the large launch vehicles. The measurement of high frequency (up to 10,000 or even 20,000 cycles per second) instability phenomena in the combustion chambers of these motors requires sensing elements to be immediately adjacent to the intense heat of the combustion process, although protected by a coolant, usually water. In the future much more severe conditions resulting from even higher pressures and heat fluxes will result in further increases in the difficulty of the rocket combustion pressure measurement problem. The research from which these target characteristics were developed is aimed, in part, at improvement of the transducers available at the present time as a contribution to the accurate measurement of current large rocket combustion pressure transients, and it is, in further part, devoted to the more difficult problems of the future.

b. Environmental Requirements

Transducers utilized in measurements of transient combustion pressures in rocket motors are exposed to very severe environmental conditions. Combustion heat (above 5000°R) and vibrational accelerations (often in excess of 100g and of the next higher order under starting and instability conditions) represent the basic environment. To these are often added ambient temperatures resulting from cryogenic propellants on the one hand to hot products from the flaring exhaust on the other. Moisture is also likely to be ever present in the local environment that the transducer must withstand and it is often dirt and/or salt laden.

Mounting of the transducers must often be accomplished under conditions of limited access. Connections, both electrical and fluid-mechanical, must be made properly to prevent conditions detrimental to reliable operation. The application of accessory components such as trim resistors and flow filters, is desirable but must be done with discretion lest they result in decreased reliability from their own tendencies to malfunction.

2. Transduction Methods

a. General

A number of methods for generating electrical signals proportional to transient pressures have been more or less successfully utilized in transducers for rocket combustion chamber measurements, in particular bonded wire resistance strain gages, variable capacitances and piezoelectric crystals, primarily quartz. Semi-conductor strain gages are currently receiving developmental attention. The above methods and others may be applicable in obtaining the characteristics outlined herein.

b. Electrical Output

Transducers should be designed so the transient electrical output under operating conditions is free of thermal and other sensitivity changes as well as non-linearities, hysteresis, and other deleterious effects. The mechanical and heat transfer design features should not introduce electrical output errors of significant magnitude.

The following outputs are considered to be typical of the several transduction methods as applied in these transducers:
(based upon a full range pressure rating of 1500 psig)

(1)	Bonded Wire Resistance Strain Gage	0.02 mv/psi
(2)	Capacitance	0.002 $\mu\mu$f/psi
(3)	Piezoelectric (Quartz)	0.5 to 5.0 pCb/psi
(4)	Semi-conductor Strain Gage	0.3 to 3.0 mv/psi

Specially designed auxiliary equipment is to be utilized as necessary for transforming these electrical quantities into easily measurable voltages without producing spurious signals, errors, noise, etc.

3. Steady State Performance

a. Zero Drift

Drift from thermal or other (e.g., coolant pressure) effects shall be minimized insofar as practicable depending on the method of transduction. An overall zero drift rate below 0.05% of full scale per minute is highly desirable but it is understood that shifts in zero pressure output and other effects on the steady state performance may have to be accepted to obtain the more important transient and thermal capabilities.

b. Sensitivity Change

Changes in sensitivity must be prevented or compensated to a high degree so as to have minimal effect on steady state output and transient outputs as well. A sensitivity change over the full linear range that does not exceed ± 0.1% from all causes is most desirable.

c. Linearity

Variation from a linear calibration should not exceed [illegible] over the full scale range of the transducer. The calibration line should pass through zero pressure with zero output.

d. Hysteresis

The maximum hysteresis exhibited over a full scale excursion should not exceed ± 0.1% of full scale.

4. Dynamic Performance

a. Response

(1) The transducer output amplitude response ratio should not deviate more than ± 10% from unity at frequencies of 100 to 10,000 cycles per second.

(2) The rise time response to the 90% value of a step function should not exceed 10 microseconds.

b. Vibration

The transducer should not respond more than 0.2% F.S. to an acceleration of 100g in any direction from zero to 10,000 cps.

c. Damping

The damping factor should not be less than 10% of critical with 20% desired.

5. Mechanical Design

a. General

The general configuration of the transducer should be such that the active diaphragm area is flush with the wall of the chamber in which the measurement is to be made, although a slight recess is sometimes used. Because of space limitations between cooling passages, as in a regeneratively cooled rocket chamber, the diameter of the transducer shank leading to the active area should be no greater than 1/4 inch in diameter (3/8 inch max.). The transducer body and other external parts should also be kept small because of space limitations posed by adjacent flanges, components, etc. The mounting method should be that which would affect the smallest volume surrounding the transducer with adequate attention given to sealing against combustion gas or other fluid leakage.

b. Material

All external portions should be fabricated of corrosion resisting material. This requirement extends also to the internal coolant flow passages. The diaphragm material must be especially corrosion proof and of high thermal conductivity.

c. Dimensions

Target dimensions are shown on the attached outline drawing (JP24M2010A).

d. Mounting

Stresses generated in attaining the pressure seal and other such effects, such as thermal expansion of the mount should have minimal effect on the zero output and particularly on the sensitivity of the transducer.

e. Coolant Passages

The pressure rating of the cooling passages should be somewhat higher than the maximum operating pressure of the transducer. The coolant lines should terminate in female stainless steel flare fittings.

f. Electrical Connections

The electrical fittings should be water and vapor proof and located preferably at the end of a flexible shielded conduit. The electrical connector should have sufficient spare pins to permit connection of a signal in case of diaphragm burn-out, temperature or end-of-line compensation for voltage, etc.

6. Thermal Design

a. The design of the transducer diaphragm and associated coolant provisions, including the establishment of nominal coolant pressure and flow values, must be aimed at withstanding continuous exposure to fully-developed, high frequency combustion instability of longitudinal, transverse and combined modes. These conditions are represented in conventional regeneratively-cooled liquid propellant rocket motors by heat fluxes up to at least 25 BTU/in^2 sec.

b. The transducer should be designed and utilized so that burn-out of the diaphragm will not allow the escape of combustion gases.

7. Reliability

EVERY EFFORT MUST BE [illegible] TO [illegible] THE HIGHEST RELIABILITY THAT PRESENT TECHNOLOGY CAN PROVIDE.

8. Miscellaneous

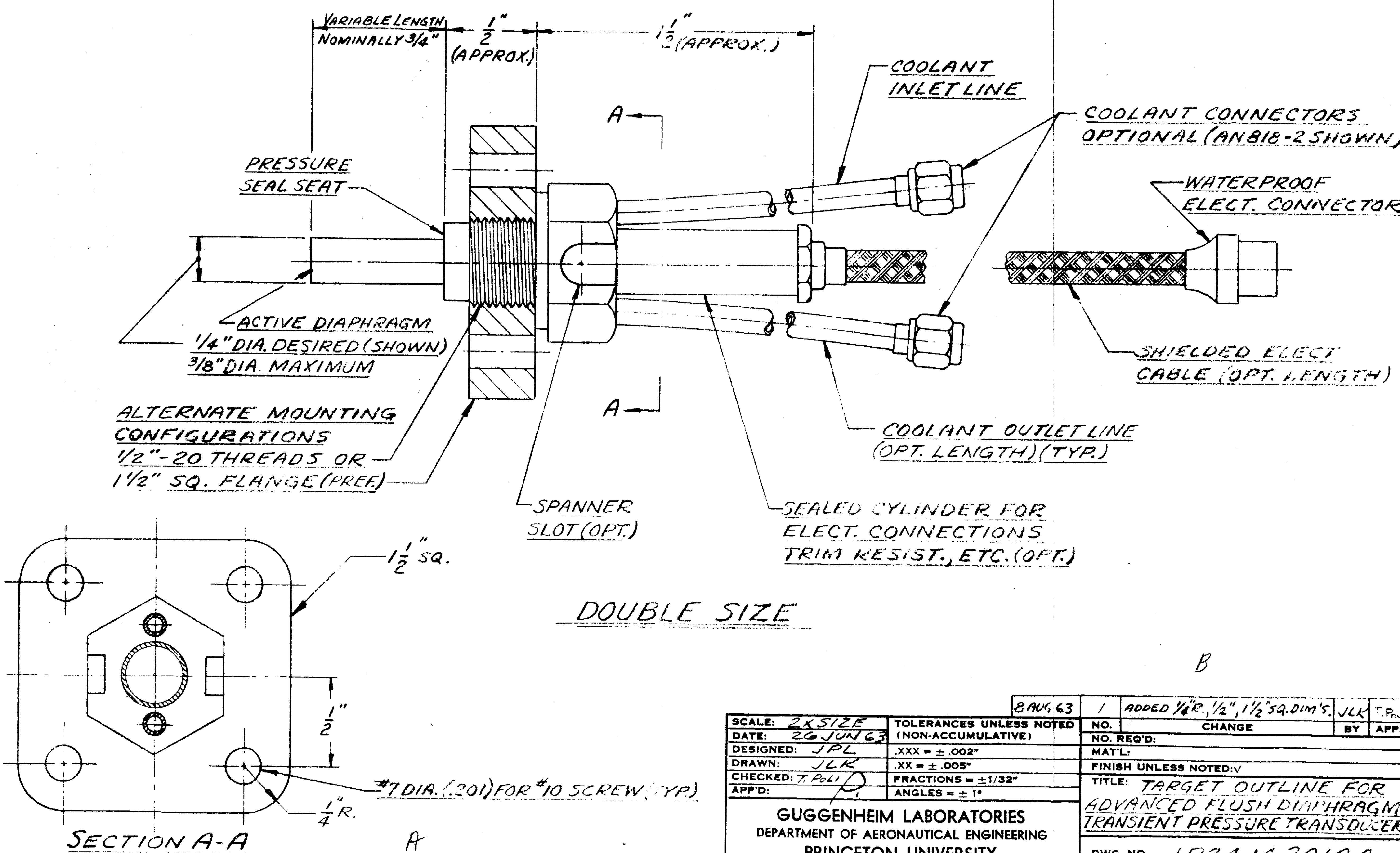
a. Calibrations

Calibration data should be provided with each transducer to establish its behavior against the specified performance.

b. Operating Information

Full operating instructions that do not assume complete familiarity with the transient transducer handling and [illegible] need to be provided with each transducer.

NOTE:-
SAFETY WIRE OR LOCK ALL THREADED PARTS.



DOUBLE SIZE

	8 AUG 63	1	ADDED 1/4"R., 1/2", 1 1/2" SQ. DIM'S.		JLK	T. Poli
SCALE: 2x SIZE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE		BY	APP.
DATE: 26 JUN 63		NO. REQ'D:				
DESIGNED: JPL	.XXX = ± .002"	MAT'L:				
DRAWN: JLK	.XX = ± .005"	FINISH UNLESS NOTED: ✓				
CHECKED: T. Poli	FRACTIONS = ±1/32"	TITLE: TARGET OUTLINE FOR ADVANCED FLUSH DIAPHRAGM TRANSIENT PRESSURE TRANSDUCER				
APP'D:	ANGLES = ± 1°					

GUGGENHEIM LABORATORIES
DEPARTMENT OF AERONAUTICAL ENGINEERING
PRINCETON UNIVERSITY

DWG. NO. JP24 M 2010A

A B

FORM NO. 3765-2 D & W BLUEPRINT CO.

APPENDIX E: Pressure and Vel[illegible] [illegible] [illegible]-Type Co[illegible] Passage

Passage cross secti[illegible] [illegible]ctangular and flow area is considered as an equivalent [illegible] A_e.

Calculating theore[illegible] velocity for the section usi[illegible] the continuity equation, $V =$ [illegible]

The theoretical veloc[illegible] and a curve of friction fac[illegible] vs Reynold's number are used to d[illegible] the [illegible] lost to frict[illegible]

$$h_f = f \frac{L}{D_e} \frac{V^2}{2g}$$ (D[illegible]sbach formul[illegible])

Other losses* are:

$h_L =$ [illegible] for 9[illegible] turns

$h_{ex} =$ [illegible] for sudden enlargement

$h_c =$ [illegible] for sudden contractio[illegible]

*King's Handbook of Hydraulics, McGraw-Hill Pub. Co.

Consider section I of the maze.

$\text{Length of section} = 0.[illegible]84 \text{ in., Width} = .045 \text{ in.}$

$\text{Depth} = 0.089 \text{ in., Wet Perimeter} = 0.268 \text{ in.}$

$D_e = 0.268/\pi = 0.0[illegible] \text{ in., Area } A = 57 \times 10^{-4} \text{ in.}^2$

$Q = 0.055 \text{ lb/sec} = 0.882 \times 10^{-3} \text{ ft}^3/\text{sec.}$

$V_1 = 144 \; (0.882 \times 10^{-3}) / 57 \times 10^{-4} = 22.25 \text{ ft/sec.}$

$R_e = \frac{V_1 D_e}{\nu} = 15,000, \text{ where } \nu \text{ at } 70^{\circ}F = 1.059 \times 10^{-5} \text{ ft}^2/\text{sec.}$

Choosing a curve for average commercial pipe,

$$f \approx 0.0[illegible]9$$

$$\text{Velocity head } V_1^2/2g = 7.7 \text{ ft}$$

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = 3.11 \text{ ft or } 1.37 \text{ psi}$$

For 90° turn into section, K varies from 0.5 to 0.75, say, 0.65.

$$h_L = 0.65(7.7) = 5 \text{ ft or } 2.2 \text{ psi}$$

Total pressure loss for section = 8.11 ft or 3.57 psi

A more realistic average velocity can now be calculated for the section.

$$V = \sqrt{2gH} = 22.8 \text{ ft/sec.}$$

Using the same procedure for the remaining sections of the maze, the total pressure drop is 15.6 psi with an average velocity of 17.7 ft/sec. in the center section. From previous flow data, the pressure drop across the maze was 14 psi for a flow rate of 0.055 lb/sec of water at $70^{\circ}F$.

N O T I C E

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